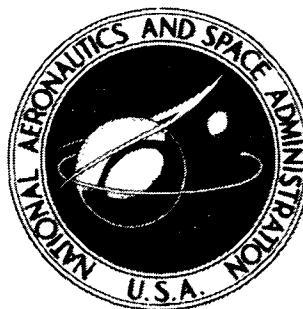


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**AN INVESTIGATION OF OPTICAL FEEDBACK  
TO EXTEND THE FREQUENCY RESPONSE  
OF SOLID-STATE DETECTOR SYSTEMS**

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# AN INVESTIGATION OF OPTICAL FEEDBACK TO EXTEND THE FREQUENCY RESPONSE OF SOLID-STATE DETECTOR SYSTEMS

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## SUMMARY

A primary limitation of many solid-state photodetectors used in electro-optical systems such as the facsimile camera is their slow response in converting light intensities into electrical signals. An optical feedback technique is presented which can extend the frequency response of systems that use these detectors by orders of magnitude without significantly degrading their signal-to-noise performance. This technique is analyzed to predict improvement, implemented, and evaluated to verify analytical results.

## INTRODUCTION

Only a few types of solid-state detectors currently available for electro-optical systems such as facsimile cameras would allow angular resolution of a few tenths of a degree or less with a wide depth of field constraint. The most important four are silicon (Si), lead sulfide (PbS), lead selenide (PbSe), and cadmium sulfide (CdS) photoconductors. All these diodes are operable at room temperature, silicon covering the wavelength range of 0.4 to 1.1  $\mu\text{m}$ , lead sulfide the range of 1.0 to 3.5  $\mu\text{m}$ , lead selenide the range of 1.0 to 4.5  $\mu\text{m}$ , and cadmium sulfide the range of 0.3 to 0.5  $\mu\text{m}$ . However, all these detectors, except silicon, have slow internal response which severely limits their application when rapid scanning is required. A thorough discussion of these detectors and their limitations can be found in reference 1.

What is required is a technique for the simple extension of detection frequency response into the low kilohertz range which covers those frequencies generated by typical facsimile camera systems without appreciable degradation of noise performance.

The purpose of this paper is to present an optical feedback preamplifier technique which, without significantly increasing noise, can significantly extend the bandwidth of photoconductive light sensors that are normally limited by internal response time. Special attention will be directed to lead sulfide because of its great importance as an infra-

red sensor. An experimental model will also be described, and test results will be presented to verify the analysis.

## SYMBOLS

A	amplifier gain
$D^*$	detectivity, $\text{cm-hertz}^{1/2}/\text{watt}$
f	frequency, hertz
G	light-dependent conductance of photodetector, mhos
$G_\lambda$	conductance of photodetector, mhos
$G_{\lambda,0}$	dark conductance of photodetector, mhos
$I_{dc}$	average current of light-emitting diode, amperes
$I_{N,f}$	rms noise current generated by light-emitting diode, $\text{amperes}/\text{hertz}^{1/2}$
$I_{N,PbS}$	rms noise current generated by lead sulfide photodetector, $\text{amperes}/\text{hertz}^{1/2}$
K	first-order frequency-dependent incremental sensitivity of photodetector, $\text{mhos}/\text{watt}$
$K'$	second-order frequency-dependent incremental sensitivity of photodetector, $\text{mhos}/\text{watt}^2$
L	light power, watts
$L_e$	effective bias radiant power, watts
$L_f$	optical feedback power, watts
$L_i$	video radiant power, watts
$L_N$	rms radiant noise of light-emitting diode, $\text{watts}/\text{hertz}^{1/2}$

$q$	electronic charge, $1.6 \times 10^{-19}$ coulomb
$R_B$	amplifier bias resistance, ohms
$R_D$	diode series resistance, ohms
$R_f$	feedback resistance, ohms
$S_D$	feedback-light coupling factor, watts/ampere
$V$	supply voltage, volts
$V_B$	amplifier offset bias, volts
$V_O$	output signal, volts
$V_S$	detector bias, volts
$\alpha$	normalized relative spectral responsivity of photodetector
$\lambda$	radiation wavelength, $\mu\text{m}$
$\Delta$	increment

Subscript:

max            maximum

## ANALYTICAL MODEL

A circuit that can improve video bandwidth by the optical feedback technique is shown in figure 1. This circuit consists basically of a high-gain light-to-voltage converter with the frequency-limited nonlinear photoconductor inside the feedback loop. The feedback element in this case is an infrared-emitting diode whose light-out versus current-in characteristic is linear over several decades.

The relations governing the basic operation of this system will now be described. The following standard equation describes the output of the operational amplifier (see ref. 2):

$$-V_O = V_S R_f G_\lambda + V_B \frac{R_f}{R_B} \quad (1)$$

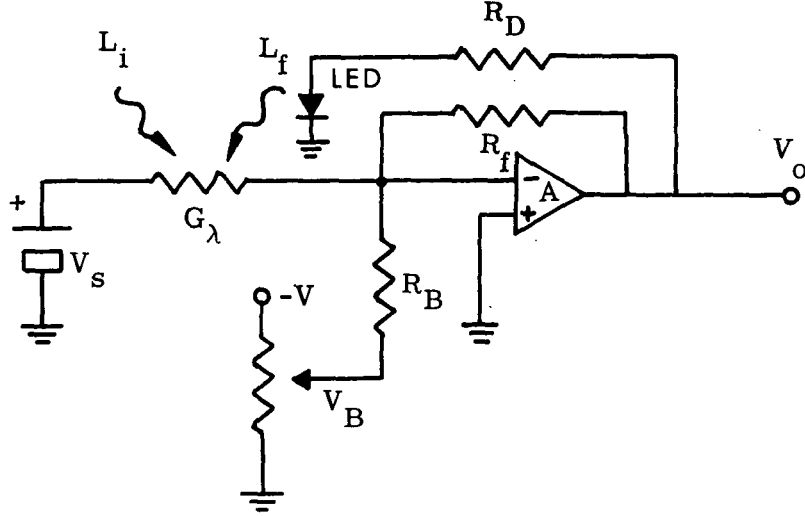


Figure 1.- Optical feedback concept.

where  $G_\lambda$  is the conductance of the photodetector, and the other factors are as shown in figure 1. (The Laplacian operator for the frequency-dependent terms is assumed.)

The next step is to introduce an artifice into this equation which eliminates the dark conductance of the photoconductor:

$$-V_o = V_S R_f G_{\lambda,0} + V_S R_f (G_\lambda - G_{\lambda,0}) + V_B \frac{R_f}{R_B} \quad (2)$$

The difference  $G_\lambda - G_{\lambda,0}$  is only a function of the light on the PbS photoconductor and is zero for zero incident light. This difference can be rewritten as the functional relationship

$$G_\lambda - G_{\lambda,0} = G(\alpha L_i, L_f) \quad (3)$$

to demonstrate the effect of the two light sources: input and feedback. Although  $G_\lambda$  is quite nonlinear, it is assumed to be monotonic. The factor  $\alpha$  is the normalized relative spectral responsivity of the photodetector, or more precisely the relative response of the photodetector to the incident light  $L_i$  as compared with its response to the feedback light  $L_f$  from the light-emitting diode. The effect of the light-emitting diode may be included in the form

$$L_f = \frac{S_D}{R_D} V_o \quad (4)$$

where  $S_D$  is a coefficient which describes the radiant power (watts) incident on the photodetector as a function of the current (amperes) into the diode, and includes, therefore, the geometry between diode and photodetector. Substituting equation (4) into equation (3) and combining with equation (2) yields

$$-V_o = V_s R_f G_{\lambda,0} + V_s R_f G \left( \alpha L_i, \frac{S_D}{R_D} V_o \right) + V_B \frac{R_f}{R_B} \quad (5)$$

Equation (5) may be linearized around the operating point  $G_{\lambda,0}$  to make it take a form more like a standard feedback system:

$$-V_o \approx V_s R_f G_{\lambda,0} + V_s R_f K \Delta L + V_B \frac{R_f}{R_B} \quad (6)$$

where  $\Delta L = \alpha L_i + \frac{S_D}{R_D} V_o$  and  $K$  is defined in the expansion of equation (7):

$$\begin{aligned} G_{\lambda} - G_{\lambda,0} &= G \\ &= \frac{dG}{dL} \Delta L + \frac{1}{2} \frac{d^2 G}{dL^2} (\Delta L)^2 + \dots \\ &= K \Delta L + \frac{1}{2} K' (\Delta L)^2 + \dots \end{aligned} \quad (7)$$

Both  $K$  and  $K'$  carry the frequency dependence of the photoconductor. Rewriting equation (6) with a little manipulation gives, to first order,

$$V_o = - \frac{V_s R_f G_{\lambda,0} + V_B \frac{R_f}{R_B}}{1 + V_s R_f K \frac{S_D}{R_D}} - \frac{V_s R_f K \alpha L_i}{1 + V_s R_f K \frac{S_D}{R_D}} \quad (8a)$$

If the loop gain  $V_s R_f K \frac{S_D}{R_D}$  is much greater than unity, equation (8a) becomes

$$V_o = - \frac{1}{R_f V_s} \left( V_s R_f G_{\lambda,0} + V_B \frac{R_f}{R_B} \right) \frac{R_D}{K S_D} - \frac{R_D}{S_D} \alpha L_i \quad (8b)$$

or, more conveniently,

$$V_o = - \frac{R_D}{S_D} \alpha L_i - \frac{R_D}{S_D} L_e \quad (8c)$$

where

$$L_e = \frac{1}{K R_f V_s} \left( V_s R_f G_{\lambda,0} + V_B \frac{R_f}{R_B} \right)$$

The formulation given by equation (8c) reveals two important points:

(1) The only sensitivity to the photodetector frequency response is in the removable constant term  $L_e$ . For this configuration, until the loop gain approaches unity the input-output frequency response to light will be determined by the feedback diode frequency response (which is generally flat to several megahertz). As the loop gain approaches unity, the input-output response will again be dominated by the photodetector frequency response. Put another way, the product of system gain and bandwidth for a high loop gain is constant. Thus, a loop gain of 10 will increase the "detection" frequency response by a factor of 10 over that of the photoconductor itself, while a loop gain of 100 will increase frequency response by a factor of 100, and so on.

(2) The output voltage is linear with respect to the input light  $L_i$ . This result represents the familiar linearizing effect of feedback. Although important, this result is not as critical as poor frequency response in the detection of low light levels commonly encountered in facsimile cameras, and it is not further pursued here.

## EXPERIMENTAL MODEL AND RESULTS

### Frequency Response

The validity of the analytical results was tested by implementing the schematic system shown in figure 1. A current-boosting transistor was used to augment a KM-47C operational amplifier output to drive a Texas Instruments PEX1206 light-emitting diode. The photodetector used was a Santa Barbara Research Center lead sulfide detector whose frequency response and spectral sensitivity characteristics are illustrated in figure 2. The detector has a nominal 0.4-megohm dark resistance, while its peak sensitivity is 0.315 mho/watt at a wavelength of  $2.4 \mu\text{m}$ . The light-emitting diode radiates at  $0.93 \mu\text{m}$ , at which wavelength the PbS sensitivity is down by a factor of about 2. Furthermore, the diode radiates into an angle of about  $130^\circ$ . For good coupling between the diode and

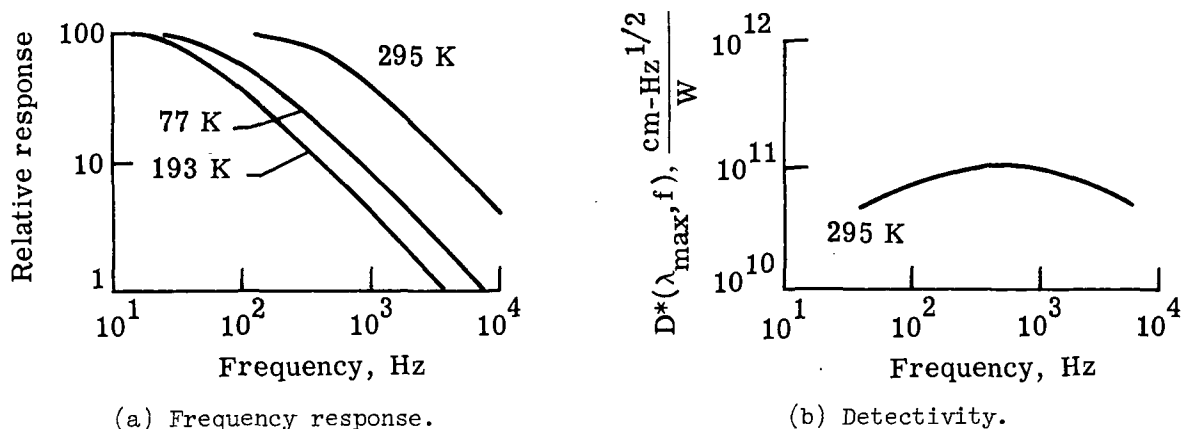


Figure 2.- Characteristics of lead sulfide photoconductor.



the 1/2- by 1/2-mm PbS detector, a separation of 1/2 cm was used. The diode and detector were inclined 45° to each other. The diode itself is specified to generate  $6 \times 10^{-2}$  watt/ampere. The operational amplifier configuration was designed to develop  $V_o$  across a 15-ohm resistor in series with the feedback diode. The actual test circuit is illustrated in figure 3.

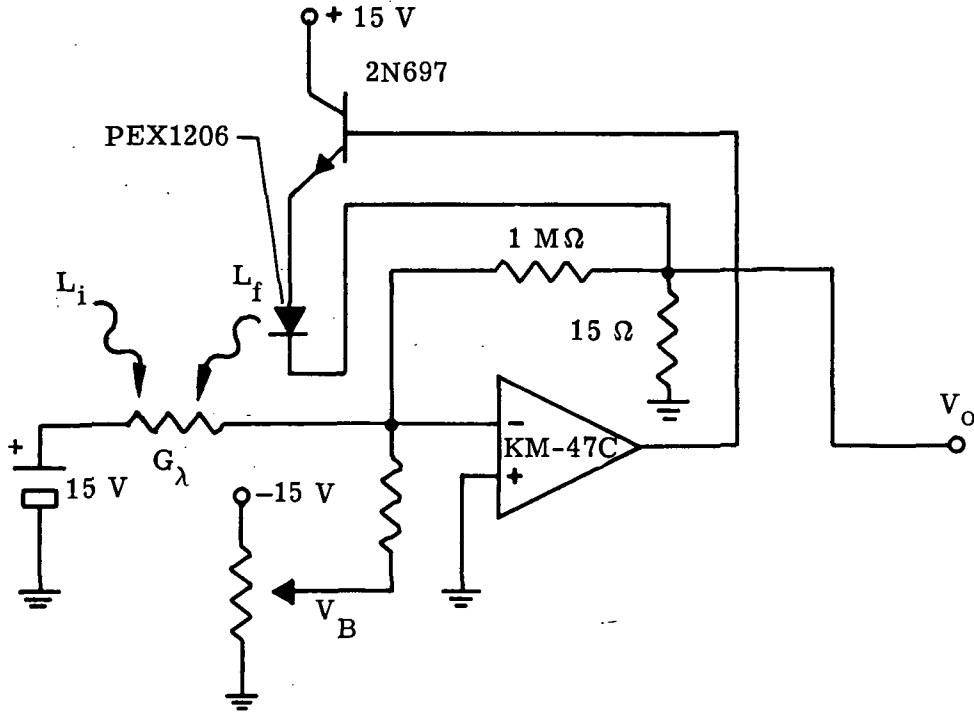


Figure 3.- Optical feedback circuit.

These considerations allow the values for the coefficients in equations (8) to be set as

$$S_D = \frac{6 \times 10^{-2} \times \frac{1}{2} \times \frac{1}{2} \times 10^{-2} \times \sin 45^\circ}{2\pi \times \frac{1}{2} \times \frac{1}{2}}$$

$$= 6.7 \times 10^{-5} \text{ watt/ampere at } 0.93 \mu\text{m}$$

$$K = 0.315 \text{ mho/watt at } 2.4 \mu\text{m}$$

$$K = \frac{1}{2} \times 0.315 \approx 0.160 \text{ mho/watt at } 0.93 \mu\text{m}$$

$$R_D = 15 \text{ ohms}$$

$$R_f = 1 \text{ megohm}$$

$$V_S = 15 \text{ volts}$$

These values yield a loop gain of

$$\frac{KV_S R_f S_D}{R_D} = 10.8$$

and an open-loop gain (light-to-voltage) of

$$KV_S R_f = 2.4 \times 10^6 \text{ volts/watt at } 0.93 \mu\text{m}$$

Additionally, the 3-dB point of  $K$  is specified as 400 hertz.

In figure 4 are plotted the open-loop gain, loop gain, and closed-loop gain response. Notice that the loop gain and open-loop gain both show the cutoff associated with the PbS photoconductor at 400 hertz. In contrast, the closed-loop gain has a predicted 3-dB frequency about an order of magnitude higher at 4000 hertz.

Figure 5 shows the actual data taken to verify the model. As can be seen, the frequency response to modulated light from a mechanical chopper has been increased significantly. In fact, the 3-dB frequency has been increased by a factor of 5.6. Since a

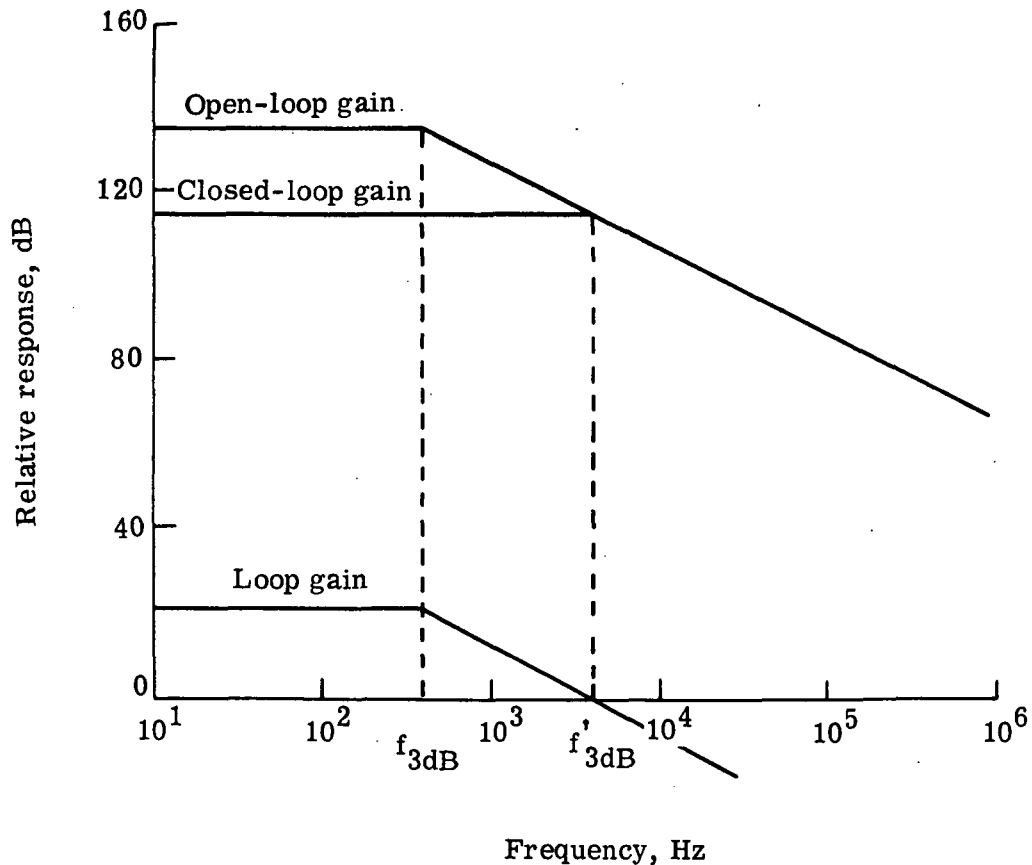


Figure 4.- Theoretical response of lead sulfide photoconductor when operated with optical feedback.

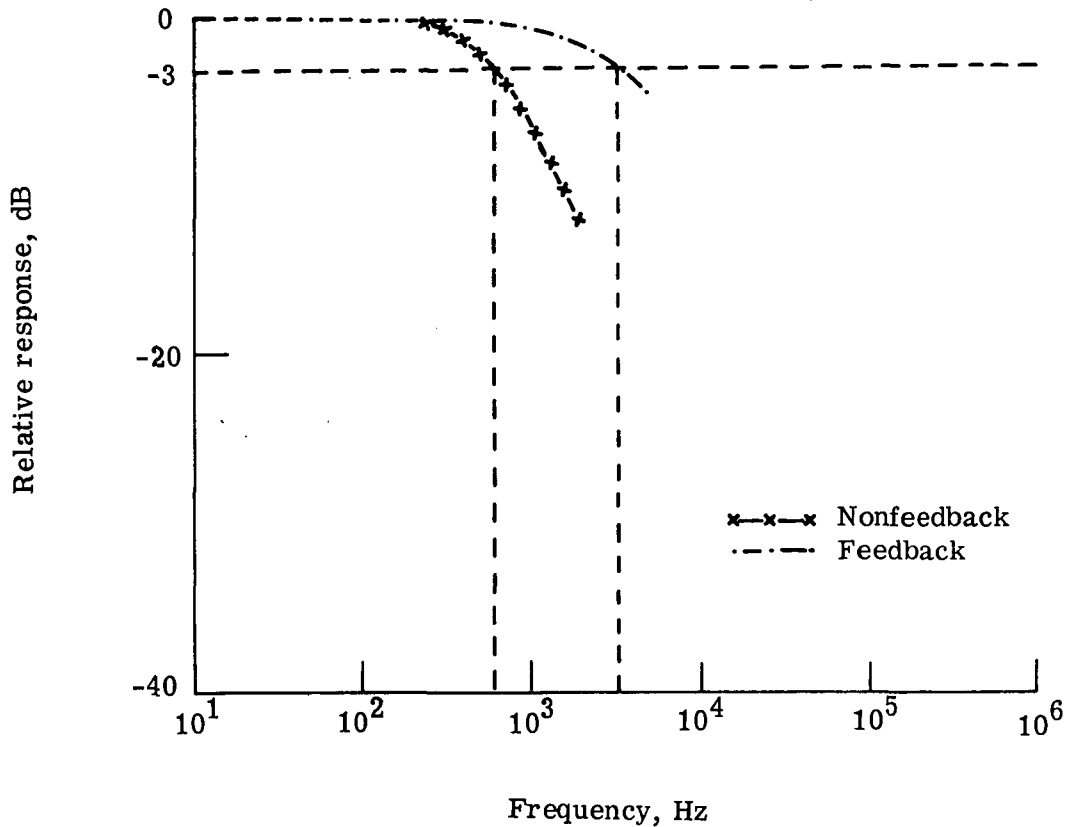


Figure 5.- Experimental response of lead sulfide photoconductor when operated with optical feedback.

trade-off between gain and bandwidth is in effect here, the factor 5.6 is approximately equal to the loop gain of the amplifier and is not too far from the 10.8 predicted by the approximate calculations.

#### Noise and Detectivity Considerations

The feedback technique used here should not appreciably affect signal-to-noise ratio if the noise generated by the feedback element is small and the bias light has no degrading effect. In this case, the feedback element is the light-emitting diode. As no information is available concerning the noise fluctuations in its light output, a reasonable guess must be attempted. Since the production of light in the diode comes from a generation-recombination process, it is natural to assume that the noise in the diode-emitted light will be similar to shot noise. For the present case, with diode bias currents of less than 1 ampere and electrical-power-to-light-power efficiencies of less than 10 percent, the root-mean-square fluctuations in emitted light should amount to

$$L_N \approx 0.1 \sqrt{2qI_{dc}}$$

$$\leq 0.055 \times 10^{-9} \text{ watt/hertz}^{1/2}$$

The feedback-light coupling factor  $S_D$  is the product of the basic light-emitting-diode radiant power per ampere and the geometric coupling from diode to photodetector (PbS in this case). Therefore, the noise power reaching the detector is

$$\frac{S_D}{60 \times 10^{-3}} L_N \approx 5.5 \times 10^{-14} \text{ watt/hertz}^{1/2}$$

Multiplying this radiant-noise power by the PbS conversion efficiency  $KV_S$  (2.3 amperes/watt) yields a noise current of

$$I_{N,f} = 12.5 \times 10^{-14} \text{ ampere/hertz}^{1/2}$$

For comparison, the PbS internal noise is specified at approximately  $2 \mu V/\text{hertz}^{1/2}$  at 780 hertz. With an internal PbS impedance of 0.4 megohm this yields a detector-generated noise current of

$$I_{N,PbS} = 5 \times 10^{-12} \text{ ampere/hertz}^{1/2}$$

Thus, comparison of the two noise currents,  $I_{N,f}$  and  $I_{N,PbS}$ , indicates that the feedback element should contribute a negligible amount of noise to the system.

As was discussed earlier, the feedback system operates with a bias offset so that the sum of feedback light and input light is a constant. Another noise consideration is, therefore, the effect this bias level might have on the detectivity of the PbS photodetector. Since the effect of the bias light in this system is to cause a slight increase in PbS bias current, a slight decrease in detectivity may result if any change could be expected. The effect of photon noise inherent in the bias light should be negligible. Not all photodetectors have decreased detectivity with bias, and in fact other photoconductive devices show exactly the opposite effect. Each case will, therefore, have to be considered individually.

Experimentally it was observed that at 800 hertz the nonfeedback system gave  $6.0 \mu V$  of output noise in a 7-hertz bandwidth. When feedback was engaged and the same output voltage was reestablished (thus setting the same current as before in the driver transistor and PEX1206) the output noise was  $1.2 \mu V$  in a 7-hertz bandwidth. This gave a ratio of 5:1, which is the loop gain determined earlier.

In other words, the feedback system does not appreciably affect signal-to-noise ratio, since both signal and noise are attenuated equally by the loop gain, justifying the qualitative conclusions concerning system noise performance.

## CONCLUDING REMARKS

The principle of optical feedback offers a method for significantly improving the frequency response of electro-optical systems that employ photodetectors with slow

internal response. As shown theoretically and experimentally, the improvement in bandwidth can be as high as the system loop gain – a result common to operational amplifiers. Furthermore, this technique does not necessarily introduce any appreciable degradation in noise performance. Finally, although a lead sulfide photodetector was chosen for the experimental evaluation, the optical feedback technique can be applied profitably to other detectors with proper consideration of noise effects of the optical feedback element.

Langley Research Center,  
National Aeronautics and Space Administration,  
Hampton, Va., November 21, 1972.

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